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932107 001N

Technical Memorandum

INFLUENCE OF DRAG-REDUCING POLYMERS ON HYDROFOIL WAKES

Date: 1 October 1993

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ABSTRACT

The overall objective of this project was to demonstrate the plausibility of reducing or modifying hydrofoil noise through polymer ejection. A polymer ejecting hydrofoil was mounted in the Naval Undersea Warefare Center (NUWC) 12-inch water tunnel. A 1000-ppm solution of polyacrylamide was ejected through slots near the maximum thickness of the hydrofoil. The streamwise mean and root mean square fluctuation velocities and normal root mean square fluctuation velocities were measured in two planes downstream of the hydrofoil.

The conclusions are that the data support the following hypotheses: (1) the drag-reducing polymers reduce the normal velocity fluctuations in the hydrofoil boundary layers; (2) this modification of the hydrofoil boundary layers leads to a reduction of all turbulent components in the far wake, and it also leads to a decrease in the normal turbulent fluctuations in a part of the near wake; (3) the momentum deficit in a hydrofoil wake can be reduced by ejection of drag-reduction polymers. These conclusions strongly suggest that ejection of drag-reducing polymers from hydrofoils will be beneficial in reducing propulsor noise.

ADMINISTRATIVE INFORMATION

This memorandum was prepared under NUWC B&P funding.

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ACKNOWLEDGMENTS

The author appreciates the support and suggestions of coworkers, especially D. Brown and R. Philips. He also wishes to acknowledge the technical support of J. Mulherin.

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INTRODUCTION

Despite the removal of the Soviet threat, stealth remains important to underwater weapons systems. Two recent publications, "Defense Science and Technology Strategy" [1] and "From the Sea," [2] have detailed the future technology difficulties faced by the Navy. The Navy expects to have a decreasing number of weapon platforms available. Also, in operations where national survival is not immediately threatened, public awareness will not tolerate large losses of personnel and multibillion dollar submarines. These considerations dictate that the survivability of submarines is of extreme importance. This survival is complicated by the fact that future operations are likely to be performed in shallow water littoral regions where escape options are limited. In light of these concerns, weapon noise reduction has two major benefits. First, quieting a torpedo delays own platform and weapon detection by a target reducing the target's response time to launch a counter attack. Second, decreasing a torpedo's noise signature reduces the chance that a nontargeted enemy vessel can track the vehicle back to its source. This second noise concern also applies to any unmanned underwater vehicle (UUV) which may be operating in association with a submarine. Therefore, stealth remains an important consideration in future torpedo and UUV designs.

Propulsor noise presents a major obstacle to attaining quieting goals for both UUVs and torpedoes. Four hydrodynamic effects produce propulsor noise. First, turbulence in the boundary layer on a rotor or stator blade causes noise at the trailing edge. Second, a blade row will produce noise when it ingests turbulence from an upstream stator or blade row. Third, the momentum deficit in a wake ingested by a moving blade row creates unsteady forces resulting in blade and vehicle hull vibration and radiated noise. Finally, tip vortex cavitation is another potential source of noise in shallow water operations. This problem is most likely to occur on unshrouded blade rows but can also occur on isolated control surfaces. Polymers may attenuate one or all of these noise sources by controlling the flow into and through a propulsor.

In addition to overall reduction of weapon propulsor noise, polymers could also increase platform stealth by changing the signature of propulsor noise. By intermittently ejecting polymer from propulsor fins at time-varying rates, the noise signature of a platform propulsor could be time varied to confuse an enemy's remote detection ability.

BACKGROUND

There exists a significant amount of experimental evidence which suggests that polymers may be effective in reducing these noise sources. First, the ability of certain long-chain polymers to reduce drag in turbulent flows has been well established. Berman [3] reviewed many experiments in pipe and channel flows. More recent work has demonstrated drag reduction in two-dimensional boundary layers. [4, 5] The studies observed that fluctuations normal to the streamwise direction in a turbulent wall flow are damped. This damping of turbulence is expected to reduce trailing edge and turbulence ingestion noise. A reduction in the drag of a hydrofoil would decrease the momentum deficit in the wake. Therefore, the strength of the fluctuating forces on a hydrofoil moving through the wake of another hydrofoil should decrease. This reduction in fluctuating forces should reduce radiated noise. Less experimental work exists which directly studied hydrofoil. Some work has been performed to determine the effects of polymers on propulsor efficiency. [6-11] In general, the effects of polymer can either increase or decrease the efficiency of hydrofoil. Whether this change was beneficial or detrimental was a function of the hydrofoil geometry, but the mathematical representation of the geometry

dependence was never established. None of these studies characterized the velocity characteristics of the wake. This project was performed to begin to address the issue of the effect of polymer ejection on turbulent velocity characteristics, which are believed to contribute to noise generation.

Other experimental work has demonstrated that tip vortex formation can be suppressed by polymers. Fruman and Aflalo [12] showed that tip vortex cavitation can be inhibited by injection of polymer solution near the tip of a hydrofoil. Their research was based on flow visualization and velocity measurements and did not report noise results; however, a suppression of cavitation usually results in major noise reductions.

OBJECTIVES OF FY93 B&P PROJECT

The overall objective of this proposal was to demonstrate the plausibility of reducing or modifying hydrofoil noise through polymer ejection. This issue is addressed by examining the influence of polymer ejection on characteristics of the turbulence, which, as discussed above, are expected to lead to a reduction of propulsor noise. The specific objectives of the test were to evaluate the following hypotheses.

(1) Ejection of a drag-reducing polymer solution from a hydrofoil can reduce the normal velocity fluctuations in the hydrofoil boundary layers.

(2) This modification of the hydrofoil boundary layers can lead to a reduction of all turbulent components in the far wake along with a decrease in the normal turbulent fluctuations in a least part of the near wake.

(3) The momentum deficit in the fin wake can be reduced by ejecting a drag-reducing polymer solution from the fin.

EXPERIMENTAL APPARATUS

A hydrofoil was mounted in the water tunnel located at the Naval Undersea Warefare Center (NUWC) Division Newport. A schematic view is shown in figure 1. The hydrofoil had an NACA 0012 profile with a cord length of 15.1 inches (385 mm) and with a maximum span of approximately 7 inches (178 mm), it extended out through the side wall boundary layers, and it was modified to eject polymer solution into the boundary layers on its sides as shown schematically in figure 2. The flush-mounted ejection slots were 0.125 inch (3.2 mm) in thickness, 3.75 inches (95 mm) in length, and were set at an angle of 25 degrees to the fin axis. The length was limited so that polymer was only ejected into the two-dimensional region of the hydrofoil boundary layers. Fluid was fed into the slots through a stainless steel screen and the slots themselves were filled with reticulated plastic foam to ensure spanwise flow uniformity.

INSTRUMENTATION

All velocity measurements were performed using a single component laser Doppler velocimeter (LDV) operated in forward scatter mode. A standard Thermo Systems Incorporated (TSI) fiber-optic probe produced transmitting beams. Standard TSI equipment was also used for

the receiving optics. All measurements were performed with the blue beams of an argon-ion laser (488 nm). The receiving optics collected light approximately 10 degrees of the main measurement axis to reduce optical noise. Both the transmitting and receiving optics were mounted on a TSI three-axis translation stage, which had a resolution of 0.01 mm on each axis. The translation stage was aligned parallel to the flow direction with the use of a dial gage; however, this alignment could only be performed to approximately 0.060 inch (1.5 mm). It is believed that this limited accuracy was due to a combination of deflection of the mounting platform and variations of the outer tunnel wall surface. Therefore, the relative spacing between points in any one velocity profile is very accurate; however, the uncertainty in the absolute position of the profile is 1.5 mm.

Signal processing was performed with a TSI model 1980B counter type processor. All streamwise statistics were calculated from 4096 sample sets using McLaughlin-Tiederman 1-D weighting to eliminate velocity bias. Normal velocity statistics could not be corrected for velocity bias. The water in the tunnel and the injected fluid were seeded with equal densities of silicon carbide particles.

EXPERIMENTAL PROCEDURE

The flow velocity was measured in both the streamwise direction, x, and the direction normal to the fin plane, z (see figure 1). These measurements were not made simultaneous because the LDV was a single component system. The streamwise measurements were acquired first, then the system was reconfigured to measure the normal component. During the streamwise velocity measurements, the free-stream speed at x = 1.05L was held fixed at 8.7 ft/s (2.65 m/s). The tunnel impeller speed was recorded for this speed and the impeller speed was held fixed during the normal measurements. Initially, streamwise measurements were performed at 20, 40, 60, and 80 mm in the y direction to verify that the wake was two-dimensional. These measurements were performed without injection and with water injection. Water ejection did not produce any measurable effect on the fin wake. Plots of these data and a more complete description are in the appendix.

Polymer experiments were performed with the same basic conditions. In order to avoid polymer buildup, measurements during polymer injection were performed only at y = 60 mm, well within the two-dimensional region of the wake. These latter measurements were performed at 16 points along a line between $z/t_{max} = -1.5$ and $z/t_{max} = 0.4$ at both x/L = 1.05 and x/L = 1.75. At the first plane, x/L = 1.05, these velocities were first measured before polymer injection to provide a basis for comparison. The measurements were immediately followed with measurements at the same points with polymer injection. Finally, in order to check for polymer buildup, the same profile was again measured without polymer injection. The same procedure was then used at the plane x = 1.75L. Chlorine bleach (30 ml) was injected into the tunnel between polymer injection cases in order to break down the polymer. The water was changed between the streamwise and normal velocity measurement experiments to further decrease the chance of polymer buildup.

During the drag reduction experiments, a 1000 ppm solution of Betz polymer 1120, a polyacrylamide, was ejected from the hydrofoils. The volumetric flow rate per unit span of the slot, Q_i, was 5.1 times the flow rate of the undisturbed linear sublayer, Q_s. The undisturbed linear sublayer was assumed to have an extent of $z^+ = (zu_\tau/\nu) = 5$. This ejection concentration and flow rate were chosen because Koskie and Tiederman[5] found them to be very effective at reducing frictional drag in zero and adverse pressure gradient, two-dimensional boundary layers.

EXPERIMENTAL RESULTS

The results of the velocity measurements are shown in figures 3 through 6. In all cases, velocity is normalized by the mean free-stream velocity, U_{ref}. The distance downstream from the leading edge, x, is normalized by the fin chord length, L, and the distance normal to the fin plane, z, is normalized by the maximum hydrofoil half thickness, t_{max} (see figure 1 for coordinates). The wake was located by measuring the streamwise velocity in the region between $z/t_{max} = -1.5$ and $z/t_{max} = 0.4$ at two streamwise locations, $x/L = 1.05$ and $x/L = 1.75$. At both locations, the wake was concentrated inside the region ($-0.5 < z/t_{max} < 0.5$).

Figure 3 shows the streamwise mean velocity and root mean square (rms) velocity as a function z at $x/L = 1.05$. The mean velocity deficit in the wake of the fin decreases when polymer solution is ejected. This change is expected because the frictional drag on the fin should decrease. The rms of the streamwise velocity does not decrease during polymer ejection. In fact, it increases slightly near the center of the wake. This behavior is consistent with the expected behavior of u' in the boundary layers. In boundary layers, u' has been observed to remain unchanged or to increase slightly during polymer drag reduction.[4, 5] Figure 4 shows the influence of polymer ejection on the rms normal velocity fluctuations, w', at the same streamwise location. The small offset between the peak in w' and $z/t_{max} = 0$ is believed to be caused by the uncertainty in the absolute alignment of the optical system. During drag reduction, w' decreased significantly in the region $0.1 \leq |z/t_{max}| \leq 0.5$ with a maximum reduction of approximately 45 percent. This change supports the hypothesis that the normal turbulent fluctuations are suppressed in the hydrofoil boundary layers during polymer drag reduction. The change also supports the hypothesis that polymer drag reduction will reduce the normal fluctuations in the wake; however, near the center of the wake, $0.0 \leq |z/t_{max}| \leq 0.1$, the magnitude of w' increases to the value measured before drag reduction. A slight increase appears near the centerline; however, this increase is smaller than the uncertainty of the data (7 percent). Polymers probably do not influence w' in this region because the turbulence in this small region is caused by the change in boundary condition at the trailing edge of the foil. This change in boundary conditions is a result of the geometry of the hydrofoil; therefore, it is not influenced by polymer ejection. The mean normal velocity, W, is not shown because it was nearly zero and the magnitude of any changes, which may have been caused by polymer ejection, were masked by the uncertainty in the measurement.

Figure 5 shows the influence of drag reducing polymers on the streamwise velocity statistics farther downstream at $x/L = 1.75$. At this location, a significant reduction is observed in both mean and rms streamwise velocities. Additionally, the rms of the normal velocity fluctuation, w', at $x = 1.75L$ was reduced during polymer ejection (figure 6). The reduction in u' and w' at this location supports the hypothesis that reduction of normal turbulent fluctuations in the hydrofoil boundary layers leads to overall reduction of far wake turbulence. The mean normal velocity, W, is not shown because it was nearly zero and the magnitude of any changes, which may have been caused by polymer ejection, were masked by the uncertainty in the measurement.

CONCLUSIONS OF FY93 B&P PROJECT

The conclusions of this experiment are that the data support the following hypotheses:

(1) The drag-reducing polymers reduce the normal velocity fluctuations in the hydrofoil boundary layers.

(2) This modification of the hydrofoil boundary layers leads to a reduction of all turbulent components in the far wake, and it also leads to a decrease in the normal turbulent fluctuations in a part of the near wake.

(3) The momentum deficit in a hydrofoil wake can be reduced by the ejection of drag-reduction polymers.

These conclusions strongly suggest that ejection of drag-reducing polymers from hydrofoils will be beneficial in reducing propulsor noise.

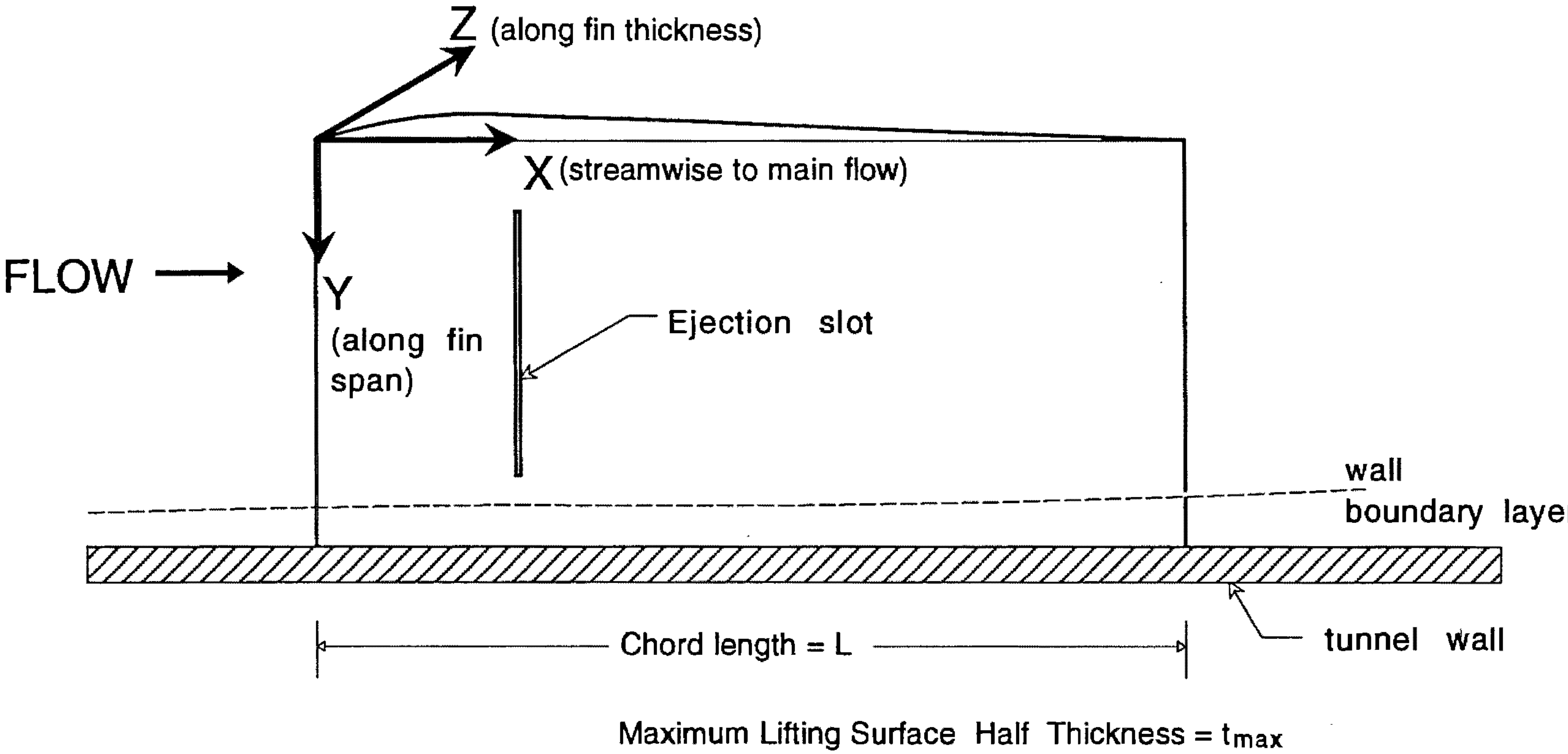

Figure 1. Schematic of Polymer Ejecting Hydrofoil Mounted on Water Tunnel Wall

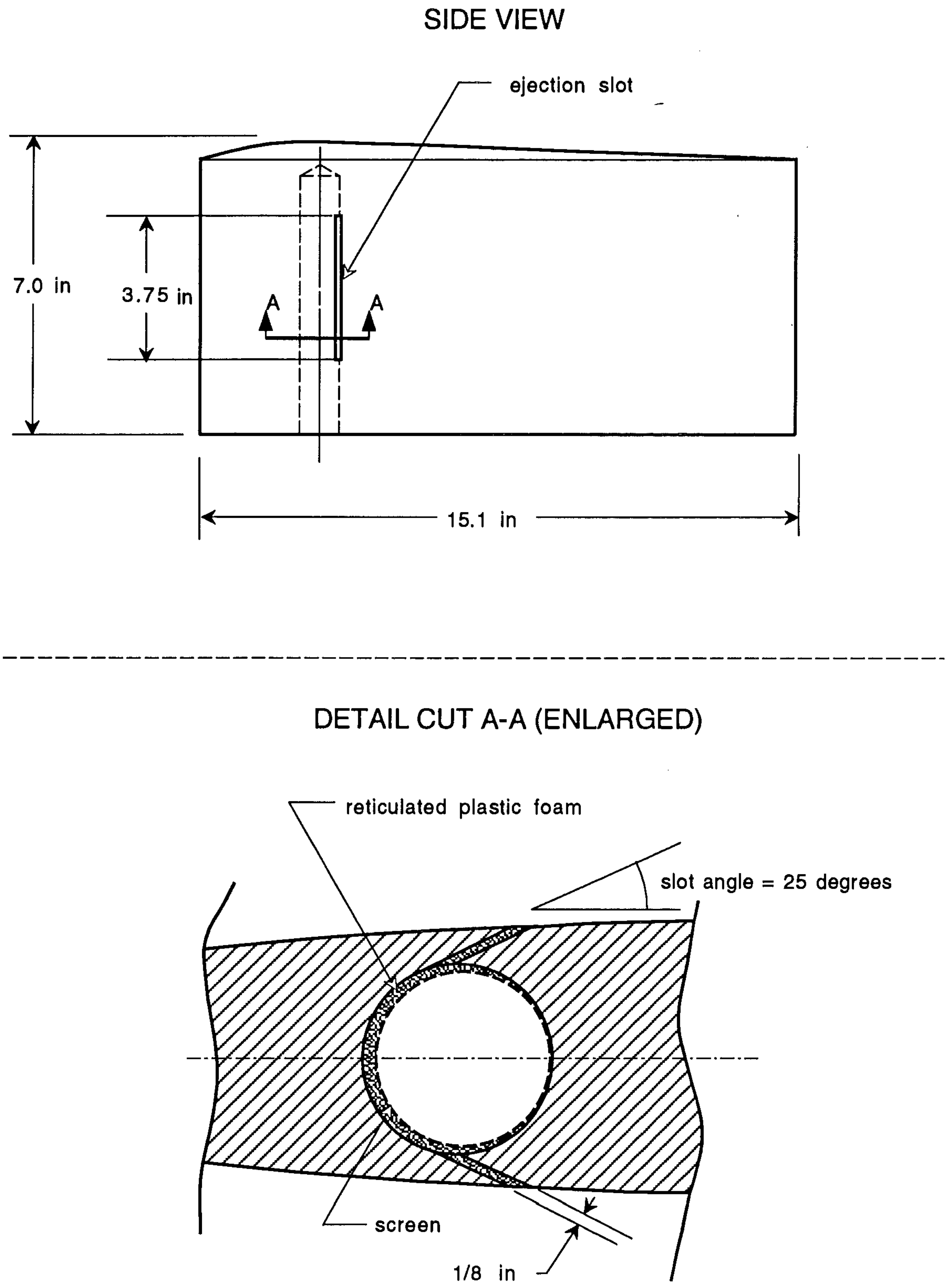

Figure 2. Schematic of Polymer Ejecting Hydrofoil

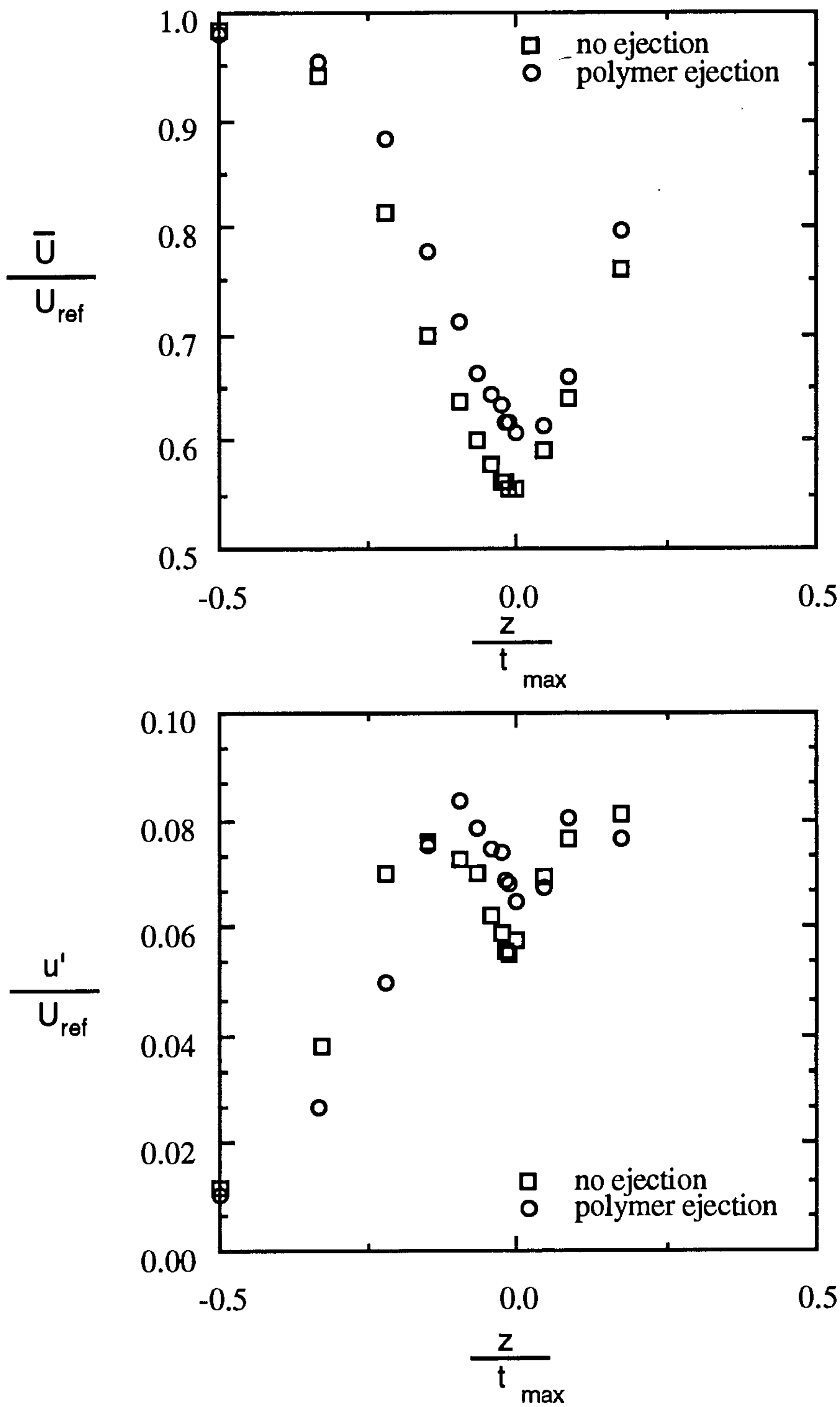

Figure 3. Influence of Polymer Ejection on Streamwise Mean and Root Mean Square Fluctuation Velocities at x = 1.05L

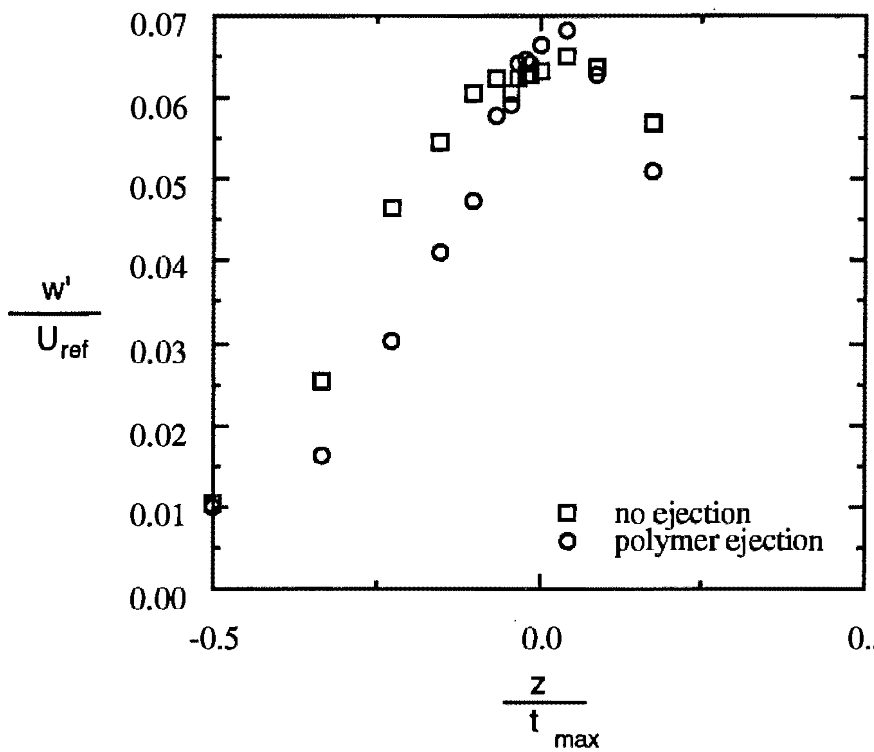

Figure 4. Influence of Polymer Ejection on Normal Root Mean Square Fluctuation Velocities at x = 1.05L

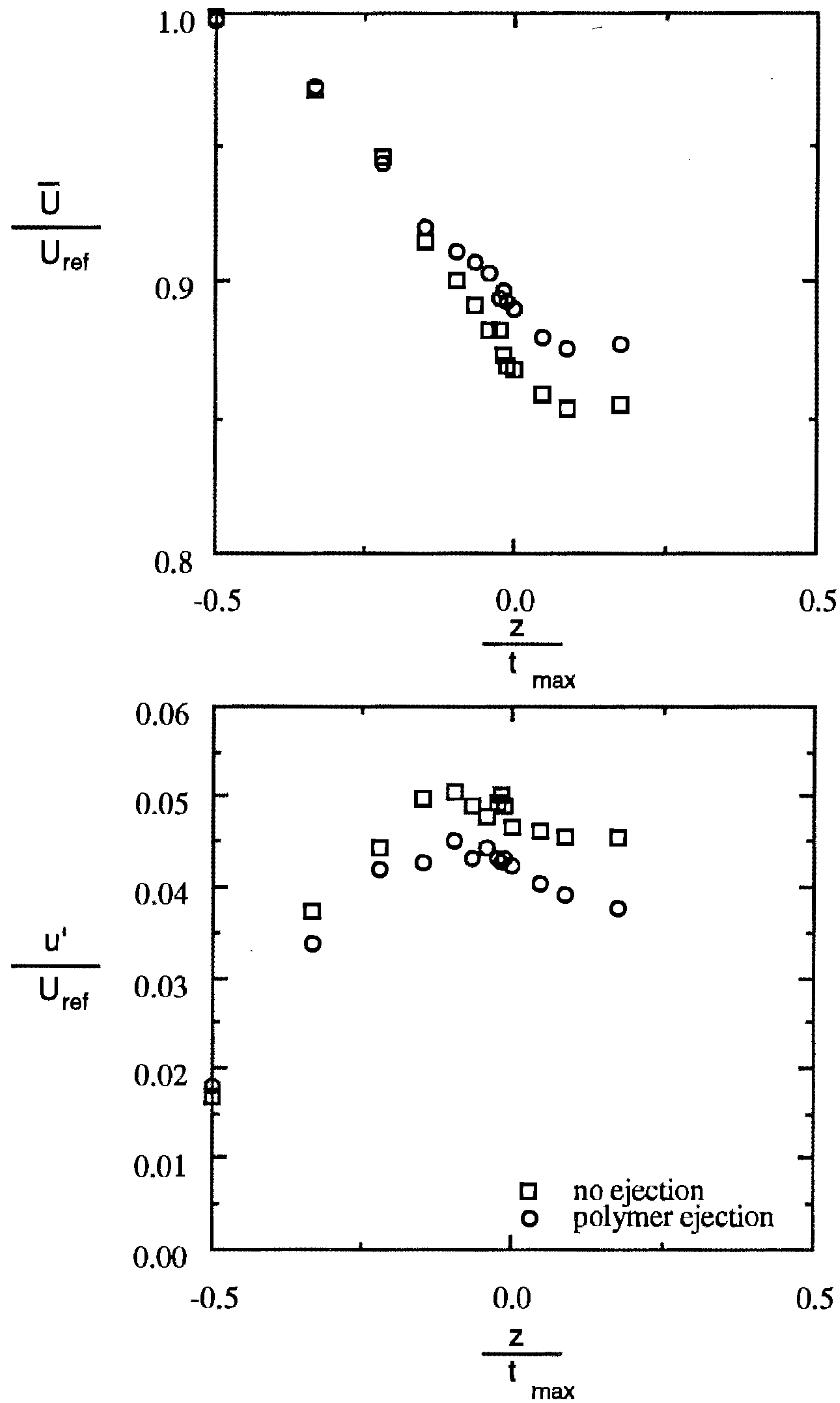

Figure 5. Influence of Polymer Ejection on Streamwise Mean and Root Mean Square Fluctuation Velocities at x = 1.75L

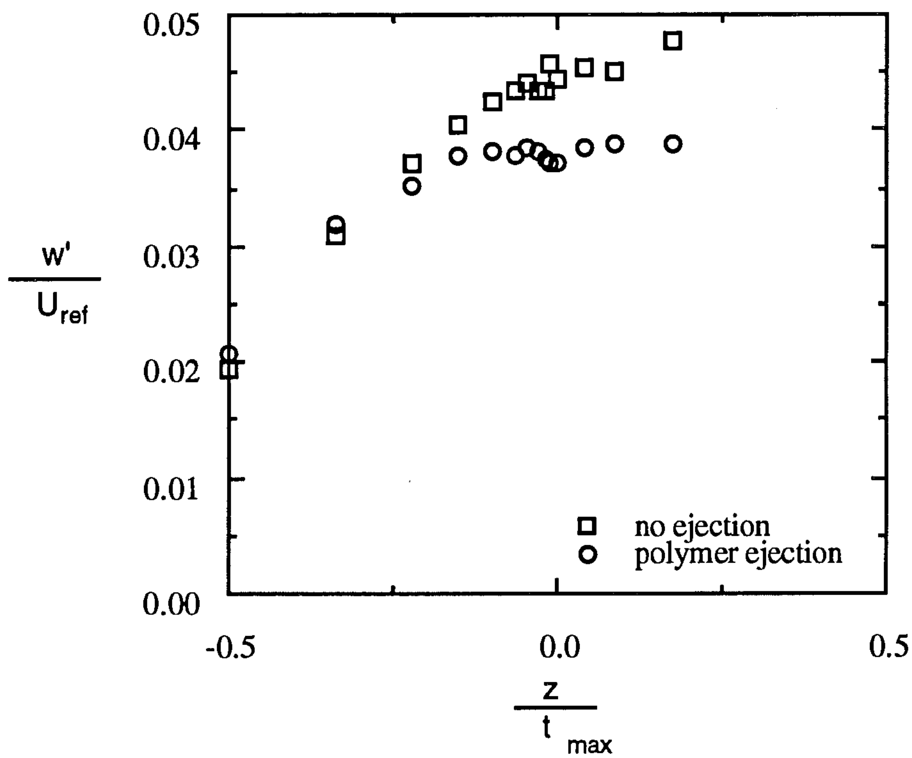

Figure 6. Influence of Polymer Ejection on Normal Root Mean Square Fluctuation Velocities at x = 1.75L

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APPENDIX A

EXPERIMENTAL UNCERTAINTY

The expected uncertainty of the data based on a 95-percent confidence level was 0.6 percent for mean streamwise velocities and 2.3 percent for root mean square streamwise velocities. For the normal velocities, the expected uncertainty is 12 percent for the mean and 2.3 percent for the root mean square fluctuations. The uncertainty is much higher on the mean normal velocity than the root mean square because the mean normal velocities are nearly zero.

ADDITIONAL VELOCITY DATA

This appendix contains plots of velocity data, which were acquired to determine the suitability of the experimental apparatus. Figure A-1 presents data acquired to determine whether a two-dimensional flow region exists in the vicinity of the ejection slots. Figure A-1 shows the mean streamwise velocity immediately upstream of the hydrofoil ($x = -0.05L$). As expected, there exists a significant potential effect from the hydrofoil on the flow at this location. When the velocity profiles at the various streamwise locations are compared, it is apparent that there is a small three-dimensional effect at the two spanwise locations nearest the end of the hydrofoil ($y = 10$ mm and $y = 20$ mm); however, in the region $40 \leq y \leq 120$ mm the velocity profiles are identical within the uncertainty of the data. The offset of $z = 0$ is believed to be a result of the uncertainty in the absolute alignment of the traverse. Part b of figure A-1 shows the same information immediately downstream of the hydrofoil ($x = 1.05L$). In this case, the wake appears uniform, at least in the region $20 \leq y \leq 80$ mm, and the three-dimensional effects, which may appear at $y = 20$ and $y = 100$ mm, are very small.

Figure A-2 examines the root mean square streamwise velocity fluctuations in the wake immediately downstream of the hydrofoil ($x = 1.05L$). Part a of the figure shows the entire measurement plane in which the data were acquired. The wake is clearly concentrated in the region $-0.5 \leq z/t_{max} \leq 0.5$ and a small offset of zero exists because of uncertainty in the absolute alignment relative to the fin. The lower part of the figure, part b, expands the wake region for more detail. These data exhibit more scatter than the mean velocity data. The scatter is somewhat larger than the expected. The reason for this increased uncertainty is not clear. Part of the variation between the spanwise locations may be a result of inaccuracies in the construction of the fin itself. The trailing edge of the fin was warped approximately $\pm$ 1 mm along its length. In addition, some of the uncertainty may be the result of short sample record times. The total sample time varied between approximately 4 seconds and 20 seconds; however, it is clear that in the region $20 \leq y \leq 100$ the root mean square streamwise velocity fluctuations in the wake are two-dimensional within an uncertainty of approximately 10 percent. The conclusion of these measurements is that a significant two-dimensional flow region exists around the hydrofoil. This region corresponds with the spanwise location of the slots.

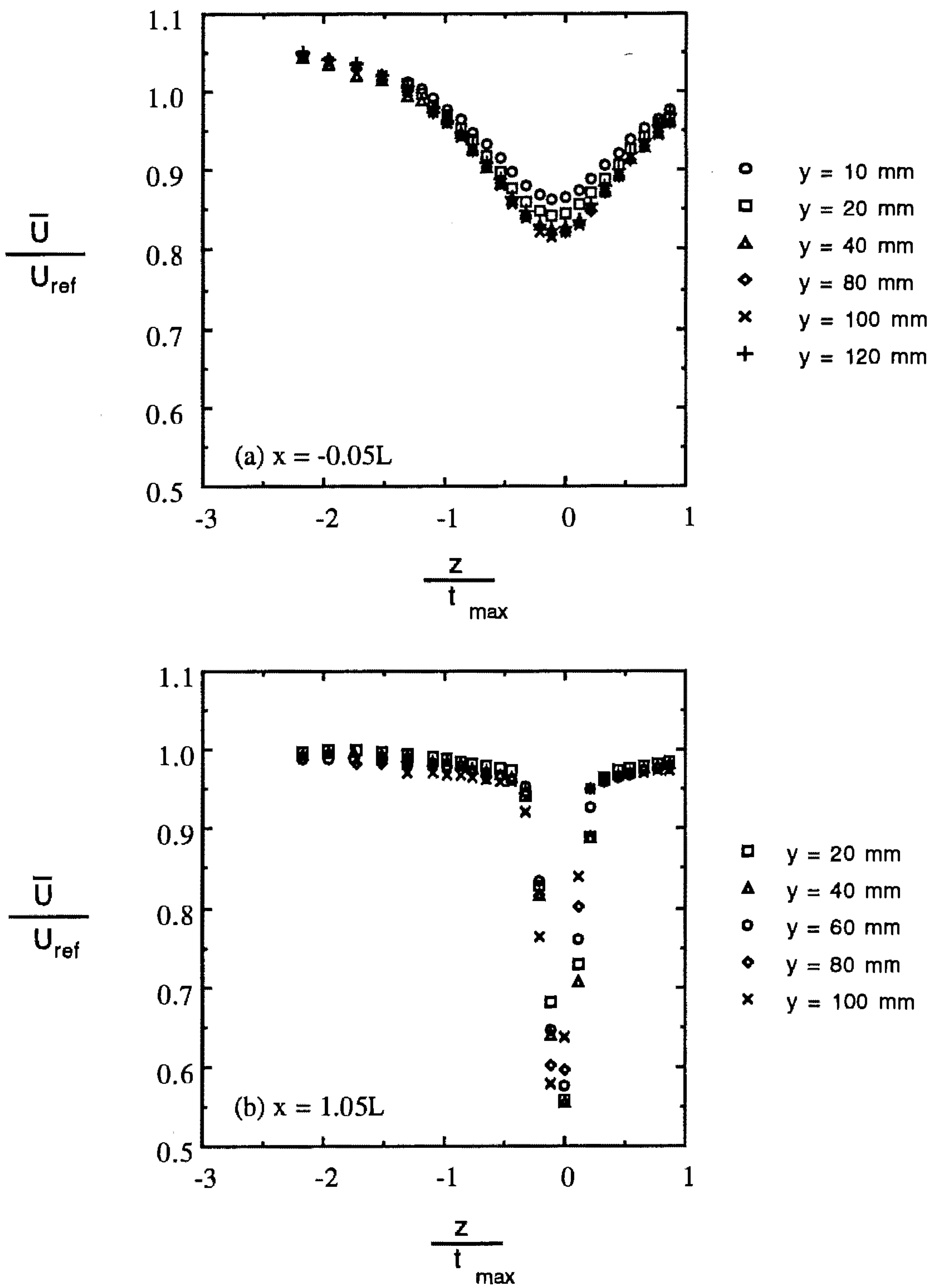

Figure A-1. Test of Mean Velocity Uniformity at (a) x = -0.05L (b) x = 1.05

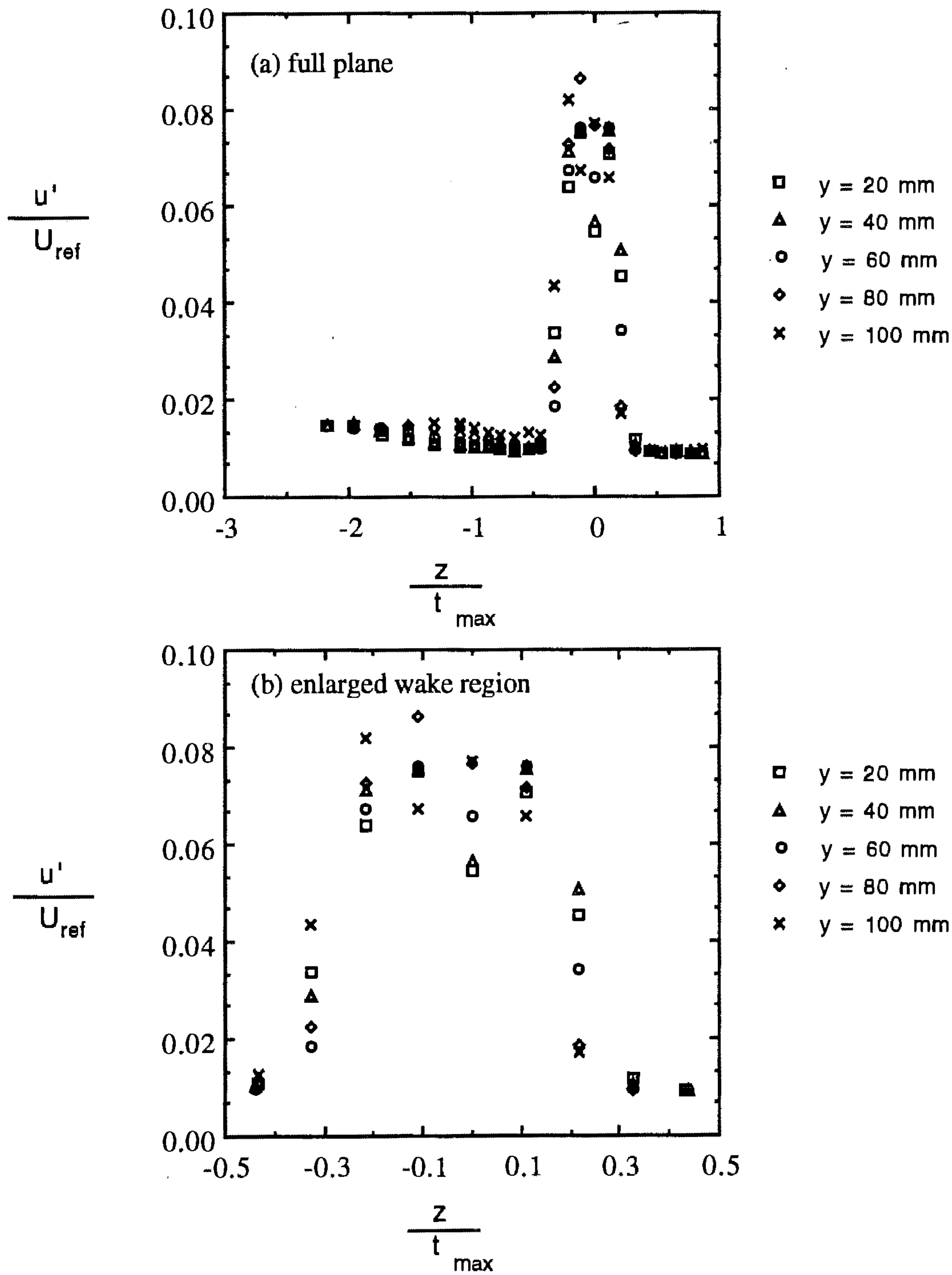

Figure A-2. Test of Root Mean Square Velocity Uniformity at x = 1.05L
(a) Full Measurement Plane (b) Wake Region Enlarged

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